Effects of Absorption by Io on Composition of Energetic Heavy Ions

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The Galileo heavy ion counter is sensitive to ions with atomic numbers $Z \geq 6$ and energies greater than ~6 MeV per nucleon. During Galileo's passage through Jupiter's inner magnetosphere, the observed composition of these heavy ions was consistent with the presence of singly ionized iogenic O, Na, and S and highly ionized solar C, O, and Ne. The solar component is absorbed more strongly by Io because its gyroradius is smaller than Io's diameter.

Results from the Voyager spacecraft encounters with Jupiter showed that energetic heavy ions form a major component of the trapped radiation in the inner magnetosphere (1). The dominant energetic heavy ions in the inner magnetosphere were O and S and most likely originate from Io, whereas in the middle and outer magnetosphere a more solar-like composition was seen with substantial amounts of C, O, Ne, Mg, Si, and Fe.

The Galileo heavy ion counter (2) provides spectral and composition information for ions with $Z \geq 6$ and with energies from ~6 to >200 MeV per nucleon. The data reported here were taken near the orbit of Io between 15:30 UT on 7 December and 01:25 on 8 December 1995 and confirm that iogenic energetic particles have low ionization states that substantially affect their transport through Jupiter's magnetosphere.

It has been commonly assumed that the energetic ions derived from Io are singly ionized, while solar particles are observed to be highly ionized (3). Because previous observations (4) have shown that the two components have different energy spectra, we report abundance ratios for S/O and C/O over a range of energies (5). Data were analyzed in two spatial regions: outside Io's orbit, from $L = 7.6$ to 6.0 inbound to Jupiter (near Io) and inside Io's orbit, from $L = 5.85$ to 4.39, where L is the McIlwain magnetic drift shell parameter (6). Io was at $L \sim 5.95$ during Galileo's flyby, but crosses L shells between ~5.9 and ~6.9 (at various magnetic latitudes) as Jupiter rotates because of the tilt of the magnetic field. The region immediately surrounding Io shows a strong absorption feature and will not be discussed here.

Inward radial diffusion and the consequent energization of the more abundant lower energy ions resulted in increasing count rates with decreasing L, except in the region dominated by the effects of absorption by Io ($6.9 \geq L \geq 5.9$). Changes in the ratios of the count rates inside of $L \sim 5.1$ indicate a flattening of the spectrum for $6.5 \leq M \leq 8.6$ GeV/G (7).

Outside Io's orbit, the C/O abundance ratio was 0.026 ± 0.007 at 16 to 17 MeV per nucleon and ≤0.05 at 6.5 to 14 MeV per nucleon, significantly smaller than the solar energetic particle (SEP) abundance ratios of ~0.4 (8). These small C/O ratios indicate that the iogenic component of oxygen dominates. At energies of 31 to 42 MeV per nucleon, C/O ratios rose dramatically to 0.29 ± 0.05, indicating that the iogenic O flux decreased more rapidly with increasing energy than did the solar component.

The S/O ratio outside Io's orbit was ~1.2 ± 0.2 in the four energy bins between 8.5 and 26.24 MeV per nucleon, much larger than the SEP ratio of 0.04 and consistent with the presence of predominantly iogenic S and O. At 43 to 48.5 MeV per nucleon, the S/O ratio decreased to ~0.38 ± 0.2, again suggesting a rapidly falling iogenic energy spectrum.

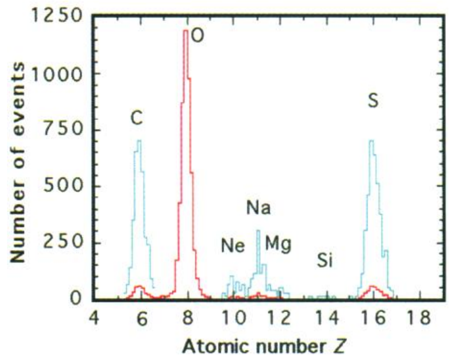

Fig. 2. Distribution of estimated nuclear charge Z for all three-detector events in the time interval shown in Fig. 1. The light blue lines are a 12.5x magnification of the data. Note that the minimum energy of these nuclei ranges from 14.8 MeV per nucleon for C to 24.5 MeV per nucleon for S.

The C/O ratio was significantly smaller inside Io's orbit than outside it (~0.007 ± 0.003 at 16 to 17 MeV per nucleon and ~0.04 ± 0.01 at 31 to 42 MeV per nucleon inside versus 0.026 ± 0.007 at 16 to 17 MeV per nucleon outside), showing that at these energies, Io absorbs the carbon ions more readily than oxygen ions as they diffuse inward. This difference indicates that the C and O ions must have different radii of gyration in the magnetic field and therefore must have different charge states (for example, close to Io a fully ionized C ion with an energy of 20 MeV per nucleon would have a gyroradius of 0.2 Io diameters, while a singly ionized O ion with an energy of 20 MeV per nucleon would have a gyroradius of 1.6 Io diameters). Conversely the S/O ratio is not significantly different inside and outside Io's orbit. Thus, weaker absorption of the iogenic O and S compared to that of fully ionized C

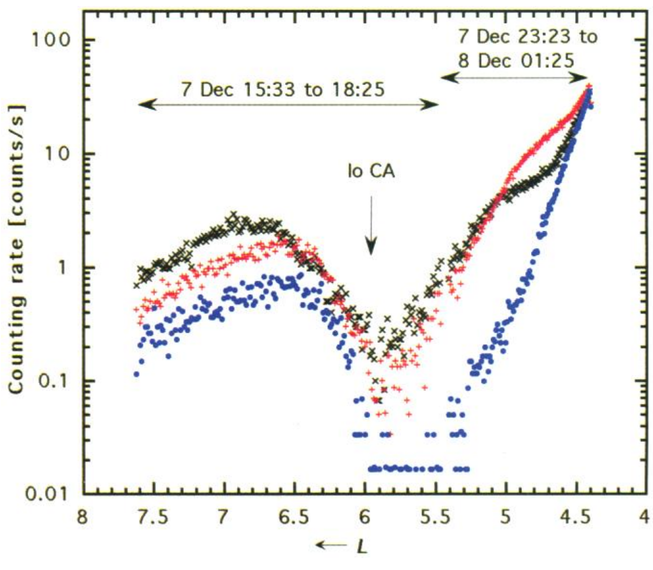

Fig. 1. Counting rates of energetic ions versus L. The counting rates are dominated by O stopping in three different, successively deeper, detectors in the HIC E telescope. The 60-s averaging interval is about three to six spacecraft spin periods, concealing the substantial spin modulation of the rates. Black crosses: two-detector events (O energies from ~16.2 to ~17.2 MeV per nucleon). Red pluses: three-detector events (~17.2 to ~27.3 MeV per nucleon); Blue circles: four-detector events (~29 to ~55 MeV per nucleon).

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indicates that they have significantly larger gyroradii resulting from lower ionization states.

REFERENCES AND NOTES

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2. T. L. Garrard, N. Gehrels, E. C. Stone, *Space Sci. Rev.* **60**, 305 (1992).
3. A. Luhn *et al.*, *Adv. Space Res.* **4**, 161 (1984).
4. See, for example, N. Gehrels, E. C. Stone, J. H. Trainor, *J. Geophys. Res.* **86**, 8906 (1981), N. Gehrels, E. C. Stone, *ibid.* **88**, 5537 (1983).
5. For this report we determined C/O abundance ratios at 8.5 to 11, 11 to 14, 16 to 17, and 31 to 42 MeV per nucleon and S/O abundance ratios at 8.5 to 11, 11 to 14, 14 to 17, 24.7 to 26.24, and 43 to 48 MeV per nucleon.
6. The L value for a drift shell in a centered dipole magnetic field corresponds to the equatorial distance (in planetary radii) of the shell from the center of the planet. The values used here were calculated by C. Paranicas and A. F. Cheng as described in *J. Geophys. Res.* **99**, 19433 (1994).
7. The magnetic moment, $M = E_\perp/B$ where $E_\perp$ is the energy associated with motion perpendicular to the magnetic field and B is the magnetic field strength. M is conserved under radial diffusion.
8. See, for example, T. L. Garrard and E. C. Stone, *Proc. 23rd Intl. Cosmic Ray Conf.* **3**, 384 (1993).

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Plasma Observations at Io with the Galileo Spacecraft

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Plasma measurements made during the flyby of Io on 7 December 1995 with the Galileo spacecraft plasma analyzers reveal that the spacecraft unexpectedly passed directly through the ionosphere of Io. The ionosphere is identified by a dense plasma that is at rest with respect to Io. This plasma is cool relative to those encountered outside the ionosphere. The composition of the ionospheric plasmas includes O^{++}, O^+ and S^{++}, S^+, and SO_2^+ ions. The plasma conditions at Io appear to account for the decrease in the magnetic field, without the need to assume that Io has a magnetized interior.

Theoretical models of the interactions of Jupiter's moon, Io, with the co-rotating magnetic field and plasma of Jupiter's magnetosphere (*1*) tried to explain magnetically field-aligned currents as resulting from a conducting Io interior and possibly from an extended ionosphere of Io and the closure of these currents in the jovian ionosphere. Earth-based observations of Io-controlled radio emissions (*2*) and the detection of a neutral Na cloud (*3*) and a torus of ionized S (*4*) provided impetus for the theoretical studies. Further considerations of the interaction of Io with Jupiter's magnetosphere found that the currents should not propagate parallel to the jovian magnetic field in the Io rest frame but at an angle determined by the local Alfvén speed (*5*). This geometry is commonly referred to as "Alfvén wings." Direct measurements of the perturbations of the jovian magnetic field in the vicinity of Io (*6*) were made by the Voyager 1 spacecraft at about 11 Io radii (R_{Io}) below Io. The magnetic perturbations were interpreted in terms of field-aligned currents in excess of 10^6 A. The discovery of active volcanic plumes (*7*) provided direct evidence that the gas and ion environment near the surface of Io is dynamic. The Galileo spacecraft has now provided additional in situ observations at Io, at a closest approach altitude of about 0.5 R_{Io} (900 km).

The Galileo Plasma Analyzer (PLS) was designed to determine the plasma densities, ion composition, and flow velocities of the jovian plasmas (*8*) as the Galileo spacecraft flew past Io. The plasma is flowing in the co-rotational direction with a speed of about 45 km s^{-1} beyond 4 R_{Io}, which is slower than the 57 km s^{-1} speed expected for rigid co-rotational motion of the jovian plasma. The largest uncertainties in this initial evaluation of flow speed, -5 to $+15$ km s^{-1}, are due to the uncertainties associated with the determination of ion composition. Further analysis will be required to determine whether the slower observed speed is due to mass loading or to inaccuracies in the initial assessment of the ion composition. At altitudes of about 1 R_{Io}, the flow velocities (Fig. 1) exhibit the signature of a classical wake for which the plasma is flowing into a void. The increased speed is due to the interaction of the jovian plasma with the neutral particles of Io's atmosphere—that is, the exchange of charges between the plasma ions and the neutrals and the acceleration of these newly born ions by the convection electric fields.

The detection of a plasma at rest relative to Io during closest approach at 17:45:46 UT was not expected. The upper limit for the flows at this time (Fig. 1) is <1 km s^{-1}. At closest approach, the ion densities increase to 18,000 ($\pm$4000) cm^{-3} and the ion temperatures decrease to about 1.3×10^5 K. For comparison, the densities and temperatures of the undisturbed torus flows at 17:35 UT are 3600 ($\pm$400) cm^{-3} and 1.2×10^6 K, respectively. The ion temperatures adjacent to the ionospheric encounter are higher than those of the torus, about 3×10^6 to 5×10^6 K, due to the charge-exchange mechanism. During the periods 17:42 to 17:44 UT and 17:48 to 17:50 UT, the spacecraft is located in the dayside and nightside wakes, respectively. The ion temperatures and energy densities are lower in the nightside wake, but they indicate that there is not a large local-time dependence for the neutral atmosphere densities as a function of altitude.

The PLS was programmed to determine the composition of plasma that was flowing in the direction of a classical wake (*8*). In the cool ionospheric plasma, at rest with respect to Io, the spacecraft ram speed was high enough to give the ions a different direction of arrival at the PLS. Nevertheless, we were able to determine the composition of the heavier ions (Table 1). Some mechanism must be responsible for the containment of the ions in the ionosphere. Otherwise the convection electric fields can be expected to sweep these ions downstream. Indeed, the thermal velocities of the cool ions are still sufficiently high, about 10 km s^{-1} relative to their escape speed from the surface of Io

Table 1. Estimates of plasma composition near closest approach to Io at 17:46 UT on 7 December 1995. The E/Q is 40 to 66 volts, and the percentage is given for the number densities. Mass is given in atomic mass units.

Mass/unit charge	Ions	Percent
8	O^{++}	15 ($\pm$5)
16	O^+, S^{++}	50 ($\pm$10)
32	S^+	30 ($\pm$5)
64	SO_2^+	5 ($\pm$2)

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